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ORIGINAL ARTICLE

Real-time control of microstructure in laser additive manufacturing

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Abstract A novel closed-loop process is demonstrated to control deposition microstructure during laser additive manufacturing (LAM) in real-time. An infrared imaging system is developed to monitor surface temperatures during the process as feedback signals. Cooling rates and melt pool temperatures are recorded in real-time to provide adequate information regarding thermal gradients, and thus control the deposition microstructure affected by cooling rates during LAM. Using correlations between the cooling rate, traveling speed, and the clad microstructure, a novel feedback PID controller is established to control the cooling rate. The controller is designed to maintain the cooling rate around a desired point by tuning the traveling speed. The performance of the controller is examined on several single-track and multi-track closed-loop claddings in order to achieve desired microstructures with specific properties. Results indicate that the closed-loop controller is capable of generating a consistent controlled microstructure during the LAM process in real-time.

Keywords Laser additive manufacturing · Real-time control · Infrared imaging · Cooling rate · Microstructure

1 Introduction

Laser additive manufacturing (LAM) involves layer by layer shaping of materials (usually in the form of powder or wire) to arbitrary configurations and geometries, using a comprehensive integration of materials science, mechatronics engineering, and laser technology. The LAM technology, which uses a high-power laser as the energy source, is regarded as an important revolution in the manufacturing industry. The technology is currently used in manufacturing and repair, cladding, design of novel alloys or functionally graded materials (FGM), and metallic rapid prototyping. LAM offers several advantages in terms of process optimization and quality of the final product over traditional deposition techniques such as arc welding and plasma spraying. LAM provides minimal dilution and distortion, smaller heat affected zone, and better surface quality or geometry control. Due to the high cooling rates, fine-grained microstructures are produced during solidification in the LAM process.

Although deposition of a broad range of metals, alloys, ceramics, and metal matrix composites (MMCs) is feasible using LAM, the performance of these materials may vary drastically with process parameters, making it difficult to tailor properties to a specific application. These properties are characterized into two main groups: (1) mechanical properties (geometry, strength, hardness, residual stress) and, (2) microstructural properties (morphology, grain size, phase precipitation, etc.). LAM involves complex non-equilibrium physical and chemical metallurgical process [1–4], which exhibits multiple modes of heat and mass transfer such as Marangoni flow, buoyancy, convection, and in some instances, chemical reactions. The majority of the current literature has focused on understanding the relationships between a material's final microstructural and physical characteristics and the conditions of solidification. Reports reveal that the complex metallurgical phenomena during LAM processing are strongly material and process dependent and governed by process parameters.

The mechanical properties of the deposited material are dependent on the solidification microstructure (grain size and morphology), which is controlled by the thermal conditions at

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the onset of solidification [5]. The grain morphology, grain size, and texture that result from solidification are controlled primarily by the thermal conditions that exist locally at the start of solidification, while the fine-scale microstructure is controlled primarily by the post-solidification cooling rate [5]. Thus, the melt pool temperature and the cooling rate are the two main parameters that govern the final microstructure during the LAM process. Therefore, these two signals need to be monitored and controlled in order to obtain a good-quality product with all the required properties.

Early reports on monitoring systems using pyrometers [6–11] indicate their feasibility in observing changes in LAM and their application to real-time process control; they also highlight the complexity of the process. Griffith et al. [12] were one of the first to apply thermal contact and imaging techniques to monitor the thermal signature during laser-engineered net shaping (LENS) processing in 1999. A thermocouple was used initially to measure melt pool temperature at different passes on a hollow block [12]. In situ temperature measurements were later performed during LENS processing using a digital infrared camera and high-speed visible data imaging, and this may be applied to LENS methods which use either powder or metal wire as the feedstock. However, no correlation was obtained for microstructural evolutions with the thermal behavior. A set of pyrometers and special diagnostic CCD-camera were applied by Doubenskaia et al. [13] for monitoring laser cladding and online measurement of the cladded layer melt pool temperature. They observed instabilities while changing operating parameters using a two-dimensional pyrometer. In a later study, Doubenskaia [14] ran a comprehensive optical diagnostic analysis on laser processing using a pyrometer and an infrared camera. A relationship between the molten pool temperature and the cladding thickness was also constructed by Hua et al. [15]. Zhang et al. [16] investigated the influence of thermal history on the microstructures and properties of a multi-layer stainless steel 410 (SS 410) thin wall. They concluded that the thermal history of a deposition has an important effect on the microstructure, and consequently on the final properties [16].

Few research groups have implemented closed-loop controllers to control the melt pool temperature in their cladding process. Song and Mazumder [17] presented a model predictive control system that controls the melt pool temperature using a dual-color pyrometer. Compensation for the lack of deposition with the closed-loop controller was demonstrated by cladding on a stepped surface. Salehi and Brandt [18] developed a PID controller to control melt pool temperature during laser cladding. The quality of clad layer in terms of its dilution and the extent of HAZ was investigated, and it was shown that control of temperature alone will not produce desired cladding results.

Although there are numerous reports available in literature on melt pool temperature measurements, there are very few researchers who have reported in situ cooling rate measurements in LAM. Griffith and Hofmeister [19] used thermal imaging and metallographic analysis to study LENS processing of 316 stainless steel and H13 tool steel. Thermal imaging was used to measure the temperature, gradient, and cooling rate around the melt pool with an offline algorithm. However, they [19] found it impractical to measure cooling rates with the thermal imaging system in real-time due to complexities of the process. Griffith et al. [19] reported cooling rate values ranging from 200 to 6000 Ks^{-1} at the solid-liquid interface. Wang et al. [20] characterized the thermal behavior of the LENS process for SS 410 single wall by using a two-wavelength imaging pyrometer. It was observed that the molten pool size and cooling rate significantly depend on the traveling speed and the laser power. Yu et al. [21] used two methods of temperature measurement for AISI 304 to make online melt pool temperature and offline cooling rate measurements.

To the author's best knowledge, no reports are available in the literature on the closed-loop control of the cooling rate or the microstructure. The motivation for the present work is to provide a method in which microstructures may be controlled in order to facilitate optimization of properties in selective areas, and to allow development of functionally graded structures. For these applications, a feedback signal is required from the microstructure to control its properties in real-time. However, there are currently no sensors available to monitor the microstructure in situ and in real-time. Thus, one needs to control the microstructure indirectly through other affecting parameters that can be monitored and controlled more easily. While in theory the cooling rate has the most significant influence on the microstructure, the complexity in capturing a real-time cooling rate signal has been a great obstacle in developing a real-time microstructure controller. There have been a couple of attempts to monitor the cooling rate in real-time; however, none were successful. In fact, there are various reports in literature that have indicated the great difficulty of real-time cooling rate calculations in LAM due to the high melt pool temperature and the rapid solidification process.

The main objective of this paper is to develop a real-time closed-loop control process to control the microstructure properties in the LAM process. An infrared-based thermal imaging system is developed to monitor the LAM thermal process in real-time. The developed system is capable of capturing the real-time cooling rate and melt pool temperature. The solidified grain structures are correlated with in situ thermal measurements to identify the appropriate procedure to control the microstructure. A novel closed-loop controller is developed to control the cooling rate in real-time. The goal is to achieve a controlled microstructure through the closed-loop control of the cooling rate. The controller's performance is evaluated for multi-track depositions with a staircase desired cooling rate. Microstructural analyses is carried out to validate the

controller's success in controlling the microstructure in at different locations with different desired properties.

An automated laser additive manufacturing (LAM) system is composed of several integrated instruments. The main components are a high power laser, powder feeder, multi-axes CNC machine or a robotic arm, nozzle, and an intelligent controller with a data acquisition system and sensors. In this section, the LAM setup configured for the purpose of this paper will be described. Information is provided on infrared imaging techniques and devices integrated to monitor the thermal history of the LAM process online.

A schematic view of the state of the art LAM apparatus used in this research is illustrated in Fig. 1.

An IPG fiber laser YLR-1000-IC operated in continuous mode with a maximum power of 1.1 kW is utilized as the energy source. A Sulzer Metco TWIN 10-C powder feeder with two 1.5 L hoppers is used to control the powder mass feed rate and the flow of argon shielding gas. The required motions are produced by a five-axis CNC machine controlled by a Fadal VMC 3016 control system. Online data is acquired and processed using a National Instruments (NI) real-time platform and Labview. An NI-IMAQ module is utilized to grab images from the infrared (IR) and charge-coupled device (CCD) cameras as input signals. The CCD images are acquired by an NI PCI-1409 (NI-IMAQ) and the IR images are acquired separately through an imaging card developed by Jenoptik. An NI Motion module is installed to apply controller signals to the system. CNC traveling speed, laser power and laser spot size are controlled using an NI PCI-7340.

The deposition powder used in the current paper is stainless Steel (SS) 303L, -325 mesh, from Alfa Aesar Co. The SS 303L powder had a composition of 17 Cr, 70 Fe and 13 wt % Ni. The specimens were sectioned in the longitudinal direction for microstructural examination. Samples were prepared using SiC grit paper with grit mesh sizes from 240 to 1200, polished with 1 μm alumina powder and auto polished with 1 to 0.5 μm diamond paste. After each polishing step, the samples were placed in an ultrasonic machine to remove contamination and later air dried. Stainless steel samples were etched in Marble's reagent (10 g $CuSO_4$ in 50 mL HCl and 50 mL H_2O), to expose grain structure and morphology. The microstructures were analyzed using optical microscopy with images obtained from an Olympus AH microscope with objective magnifications of up to 50×.

1.1 Infrared image acquisition system

In order to control the microstructure in real-time, a complete knowledge of the melt pool temperature and the cooling rate is required. To monitor these properties during solidification, a great amount of thermal information is required from the melt pool and its surroundings. There are a variety of devices including thermocouples, pyrometers, and thermal infrared (IR) cameras. As mentioned earlier, a continuous special estimation of the cooling rate is needed for the proposed microstructure control in this work. As a result, an IR camera was used to measure the temperature of the melt pool and its surroundings directly in real-time and the cooling rate of deposited material was calculated using the algorithm discussed above.

Fig. 1 Experimental setup in automated laser fabrication (ALFa) lab

In this research, a Jenoptik IR-TCM 384 camera module is used to monitor the LAM process. The camera's specifications are shown in Table 1. The IR camera is connected to the LAM setup through an IEEE-1394 interface to obtain real-time measurements of the cooling rate and melt pool temperature.

An IR camera defines the real temperature of an object using a constant emissivity value ε. The emissivity of an object is the ratio of the amount of radiation actually emitted from the surface to that emitted from a blackbody (with the same material) at the same temperature [22]. The emissivity of metallic powders deposited during LAM (such as stainless steel and titanium) are highly dependent on temperature, especially at the elevated temperatures in the LAM process (800−2000). The change of emissivity with temperature in steel is attributed to the formation of an oxide layer on the surface of the steel as its temperature increases [23]. This change of emissivity may lead to errors in capturing the real body temperature as high as 100 [24].

It may be noted that emissivity changes are not important in acquiring and analyzing thermal data for the current application. Hence, an average emissivity of 0.6 is calculated for the material (stainless steel) being deposited and this emissivity is kept constant throughout the whole process and real-time temperature calculations.

1.2 Thermography analysis and processing techniques

The IR camera module IR-TCM 384 captures infrared images of 384 × 288 pixel resolution that are collected and processed online using Labview. These images only provide temperatures of each pixel and thus, require processing and analysis to be functional for microstructural analyses and control applications.

Since the images are stored in an 8-bit gray format, each pixel has an intensity value of 0-255 which is directly related to its temperature. The camera was located at a distance of 20-25 cm from the substrate which provided a resolution of 0.5 to $0.65\frac{\text{mm}}{\text{pixel}}$. To better perform thermographic analyses, the image is converted into a two-dimensional array as shown in Fig. 2. The image array has a size of $X\times Y$ in which X is the total number of pixel rows and Y is the total number of pixel columns of the image. In case of a 384×288 pixel image, X=384 and Y=288. Each element of the array has an assigned row r, and column c, with a position vector (c,r), which is shown in Fig. 2. The size of each element $I_{c,r}$ is equal to the intensity value of the equivalent pixel.

An algorithm is required to extract melt pool temperature and cooling rate in real-time using the thermal images. By extracting the melt pool temperature and the cooling rate, enough information is provided about microstructural variations during deposition. Apart from the melt pool temperature and cooling rate, a thermal map of the neighboring points on the clad line and outside will provide additional information of the microstructural evolution. A general description of the thermal algorithm that extracts the melt pool temperature and the real-time cooling rate is discussed in the following paragraphs.

Table 1 Technical data of the Jenoptik IR-TCM 384 IR camera

Image resolution	Standard: 384×288 RE Mode: 768×576 (optional)
Interfaces	IEEE-1394 (FireWire), S-/C-Video, VGA, RS-232 Gigabit-Ethernet (option) WLAN (option)
Measuring accuracy	±1.5 K (0 °C … +100 °C), otherwise±2 K/±2 %
Spectral range	7.5 μm … 14 μm
Temperature measurement range	Standard: −40 °C … +300 °C Optional: up to +2000 °C
Temperature resolution	NETD <70 mK with filtering: NETD <30 mK

1.2.1 Measuring the melt pool temperature and cooling rate

The pixel with the maximum intensity value $I_{\max}$ in each frame, represents the melt pool. Thus, the center of the melt pool and temperature is found by identifying the center of mass for the maximum elements inside the image array.

As discussed earlier, since there are no sensors available to monitor the microstructure directly during the process, the closed-loop control process has to be achieved through other intermediate parameters affecting the microstructure. The majority of reports available in literature have identified the cooling rate as the most influential parameter on the solidification microstructure, and hence this parameter was selected to develop a successful real-time closed-loop process for the microstructure.

A brief description of the methodology used for cooling rate calculations in this paper is summarized in Fig. 3. This figure illustrates two thermal images at times $t_1=t_0$ and $t_2=t_0+n\tau$, in which τ is the sampling time and n is the total number of sampling times elapsed after initial time t_0. Point P_m is the instantaneous melt pool position (where the laser beam is currently shooting at) that has a fixed position vector (c_m,r_m) in all grabbed images. Point P_1 is a fixed point in space on the clad line. At time t_0 (Fig. 3a), the laser beam is shooting at point P_1. Thus, P_1 is located inside the melt pool with a position vector (c_m,r_m) and temperature T_m, which is the melt pool temperature. After $n\tau$ s (Fig. 3b), as the laser beam moves away from P_1, point P_1 moves out of the melt pool with a speed $v(t)$ that is the traveling speed of the CNC table. Hence, after an elapsed time ($n\tau$ s) point P_1 obtains a new position vector (c_P,r_P) in the

Fig. 2 Two-dimensional array of the IR image

image with a new temperature T_n. The two factors influencing the microstructure at point P_1 are: (1) melt pool temperature that is measured as T_m (in the previous section), and (2) cooling rate C_P. The cooling rate is defined as the amount of temperature reduction in time. For point P_1 the cooling rate is defined as:

$$C_P(t) = \left|\frac{\Delta T(t)}{\Delta t}\right| = \left|\frac{T_n(t) - T_m(t)}{n\tau}\right| \quad (1)$$

in which $T_m(t)$ is the instantaneous melt pool temperature and $T_n(t)$ is the reduced temperature of the melt pool after $n\tau$ s. Hence, the real-time cooling rate $C_P(t)$, is obtained through Eq. (1) at each sample time. Specifically, at each sample time the instantaneous melt pool temperature $T_m(t)$ is measured, and after $n\tau$ s its reduced temperature is measured to obtain the cooling rate. Thus, the cooling rate measurement system always requires a delay of $n\tau$ seconds to make correct real-time measurements.

Fig. 3 Movement of a constant point on the clad line in consecutive images

1.3 Application of thermal feedback control to LAM

The melt pool temperature and the cooling rate are the two intermediate process outputs, which will be used as feedback signals to control the microstructure throughout this research. Monitoring and processing the two signals were described in the previous Section 1.2. To obtain a desired microstructure during the LAM process, it is required to control the cooling rate and the melt pool temperature in real-time. A controller is responsible for acquiring these data and interpreting the required control actions to promote the desired material properties and microstructures. Since the output process parameters are measured and fed back to the controller in real-time, a closed-loop feedback controller is required for the current system.

The majority of reports available in literature have attributed microstructural evolutions to cooling rate variations rather than the melt pool temperature. In this paper, a PID controller is designed to control the cooling rate in a closed-loop process

Fig. 4 Block diagram representation of the novel real-time microstructure controller

Fig. 5 Multi-track claddings for evaluation of the microstructure controller

Table 2 Optimal PID gains for multi-track cladding with step set-point

Staircase set-point cooling	K_C	$T_I\left(\frac{1}{K_I}\right)$	T_D
A (850 $\frac{°C}{s}$ and 430 $\frac{°C}{s}$)	4	0.002	0

based on real-time data of the IR images. The goal is to achieve a controlled microstructure through closed-loop control of the cooling rate.

1.3.1 Controller design

Since the LAM process is a complex nonlinear system, some preliminary experiments were first conducted to understand which of the process variables should be used as the control action. The outcomes of these experiments are described in this section to provide a good choice for the control action.

Initial experiments were conducted to evaluate the effect of laser traveling speed, laser power, and powder feed rate on the cooling rate. Results indicate that the traveling speed has a more critical effect on the cooling rate value. Hence, to simplify the problem, the traveling speed was used as a single controlling action to stabilize the cooling rate to a desired value. All other affecting parameters such as the laser power and powder federate were not controlled in real-time. A PID controller was then designed and developed accordingly.

Finally, a methodology was developed to control the microstructure in real-time during the LAM process. A block diagram of the approach is presented in Fig. 4. Real-time cooling rate and melt pool temperature values are extracted from the IR images based on the thermographic algorithm discussed in Section 1.2. The target is to control output microstructural variations based on cooling rate changes during the process. The developed closed-loop control system measures the cooling rate in real-time and feeds it to a real-time cooling rate controller. The controller then feeds in the required traveling speed to reach the desired cooling rate. A controlled microstructure is expected through a controlled cooling rate at the end of the LAM process.

2 Discussion and results

This section addresses the experimental design, implementation and performance of the closed-loop PID controller for controlling the microstructure in real-time during the LAM process. As stated earlier, the traveling speed is used as the control action to control the cooling rate and thus, the deposition microstructure in real-time.

2.1 Microstructure control in multi-track cladding under thermal disturbances

A multi-track deposition test was prepared to evaluate the performance of the developed real-time microstructure controller. As shown in Fig. 5, three clad lines were deposited consecutively without any cooling in between. The length of each line is 90 mm, and the lines have a 5 mm distance between them. Thus, as each line is deposited, a certain amount of preheat is produced in the substrate, disturbing the initial thermal conditions of the system for the next deposition. Moreover, instead of having a constant set-point, a stair case set-point was assigned to the controller. The initial set-point for the first half of each line is 430 $\frac{°C}{s}$, and then the closed-loop controller has to reach a set-point of 850 $\frac{°C}{s}$. Therefore, the controller's performance is evaluated by introducing two disturbances: (1) preheat and (2) changing set-point.

Several samples were cladded by the closed-loop process with the same conditions as in Fig. 5. A set of A samples were analyzed for further evaluation of cooling rate and microstructure control. Due to the great nonlinearities of the system a

Fig. 6 Closed-loop response of cooling rate for three repeated claddings which transition from 430 to 850 °C/s cooling rates

Fig. 7 Closed-loop traveling speeds of sample A $\left(430\ \frac{^\circ C}{s}-850\ \frac{^\circ C}{s}\right)$

new set of PID gains were required for each set-point. However, it was intended to tune a single set of PID gains for the multi-track staircase set-point for the A sample, though this was difficult to achieve and required greater attention. The optimum set of PID gains tuned for the multi-track claddings with a staircase set-point ($850\frac{^\circ C}{s}$ and $430\frac{^\circ C}{s}$) are listed in Table 2.

The closed-loop response of the cooling rate for the A samples are illustrated in Fig. 6. The number (n=1, 2 and 3) after the sample number (i.e., An) indicates the deposition line (shown in Fig. 5) in each sample. There are overshoots at the beginning of the cooling rate signal, which is attributed to the nature of the real-time cooling rate measurement system. As stated earlier in Section 1.2.1, since a certain amount of delay (in this case $(n\tau)_A$=0.9375 s) is required for the calculation of the cooling rate (temperature reduction), the system requires 0.9375 s to measure the first cooling point. It can be observed in Fig. 6, after nearly 0.9375 s the overshoot is damped since the system measurements of the cooling are correct, whereas, before this time the system measurements are unreliable and incorrect. Moreover, the initial oscillations and slow convergence of the system is attributed to the absence of a T_D gain. Unfortunately, after a T_D gain was inserted into the system, although, convergence was faster, the system became unstable.

The controller is successful in achieving the desired set-points; however, there are oscillations around the initial set-point $430\frac{^\circ C}{s}$. Since $430\frac{^\circ C}{s}$ is lower than the $850\frac{^\circ C}{s}$, the oscillations are mainly considered to be noise of the measurement device due to low pixel resolution at lower cooling rates. The time delay for cooling rate calculations is the same at both low and high cooling rate regions ($n\tau$ kept constant throughout measurements). It will be observed in the later section that the lower cooling rate region has a lower traveling speed. The distance between initial and final temperature measurements for the cooling rate is calculated based on the product of traveling speed and time delay ($n\tau$). Hence, when the speed is lower, the spatial distance between the final and initial temperature measurements is less (only a few pixels). As the distance between the final and initial temperature reduces, the chances of sensor error increase since the temperature pixels are closer. Thus, the noise at low cooling rate and traveling speed is mainly attributed to low sensor resolution.

Fig. 8 Closed-loop response of the melt pool temperature for sample A $\left(430\ \frac{^\circ C}{s}-850\ \frac{^\circ C}{s}\right)$

Fig. 9 Micrographs of lines *A*1, *A*2 and *A*3 at low cooling rate (closed-loop control at 430 $\frac{°C}{s}$)

Additionally, since the optimal PID gains are assigned for the staircase set-point, which contains two cooling rate values, it has been tuned for a combination of both set-points (850 $\frac{°C}{s}$ and 430 $\frac{°C}{s}$). Thus, the PID gains do not satisfy the most optimum response for each of these set-points individually, whereas, they are tuned to produce an average good response

Fig. 10 Micrographs of lines *A*1, *A*2 and *A*3 at high cooling rate (closed-loop control at 850 $\frac{°C}{s}$)

Fig. 11 High magnification micrographs of lines *A*1, *A*2 and *A*3 at low cooling rate (closed-loop control at 430 $\frac{°C}{s}$)

for both set-points. Comparing closed-loop cooling rate responses of the lines in sample *A*, the general performance of the controller is satisfactory under disturbances.

The closed-loop traveling speeds of the *A* samples are shown in Fig. 7. All the three deposited lines in the *A* sample (*A*1, *A*2 and *A*3), have similar closed-loop traveling speeds and cooling rates. It can be noted that the lower cooling rate region (430 $\frac{°C}{s}$), has a lower stable speed compared to the higher cooling rate region (850 $\frac{°C}{s}$). Therefore, the controller's response is logically correct considering the fact that at lower

Fig. 12 High magnification micrographs of lines *A*1, *A*2 and *A*3 at high cooling rate (closed-loop control at 850 $\frac{°C}{s}$)

speeds lower cooling rate values are expected due to the higher amount of energy input.

The melt pool temperature of the *A* sample is illustrated in Fig. 8. An unanticipated finding is that the melt pool temperature of the 430 $\frac{°C}{s}$ and 850 $\frac{°C}{s}$ sections are not different. The temperature is found to be consistent, although, the cooling rate and the traveling speed are changing. This finding further supports the idea that small variations in the traveling speed do not affect the melt pool temperature, whereas, they influence the cooling rate and thus the microstructure significantly. Another hypothesis is the fact that at lower speed a larger melt pool size exists. Thus, although the melt pool temperature is equal for both the low and high traveling speed sections, the total amount of energy in each melt pool is different due to the changing dimension of the melt pool. The results indicate that the controller is able to conveniently track a desired response for the cooling rate at different set-points.

2.1.1 Microstructure control

The main aim of this research is to produce a desired controlled microstructure during the LAM process. The proposed closed-loop control process was successful in controlling the cooling rate for multi-track claddings. Preliminary studies on microstructural evolutions suggest that a controlled cooling rate during the process should yield a controlled microstructure as well. Hence, to validate the performance of the closed-loop controller on microstructural evolutions, the samples were sectioned at two locations, one in the 430 $\frac{°C}{s}$ region and the other in the 850 $\frac{°C}{s}$ region, as shown in Fig. 5. If the microstructural trends of each line in the *A* sample are similar, the controller has been successful in controlling the microstructure during the LAM process. Although the melt pool temperature also influences the final microstructure, it is expected that the real-time cooling rate of the melt pool determines its general microstructure. This effective role of the cooling rate on the microstructure can also be investigated in the lower and higher cooling rate regions of the *A* samples, which have similar melt pool temperatures but different cooling rate values.

Optical micrographs obtained from sample *A*, at low (430 $\frac{°C}{s}$) and high (850 $\frac{°C}{s}$) cooling rates are shown in Figs. 9 and 10, respectively. It is apparent that all deposited lines in *A* have consistent similar microstructures at both cooling rate regions. To better illustrate the microstructure control and consistency in the *A* samples, higher magnification micrographs of these samples are presented in Figs. 11 and 12.

Table 3 ASTM grain size number measured for the low cooling rate region, $C = 430\frac{°C}{s}$

Sample no.	*A*1	*A*2	*A*3
ASTM grain size no.	11.5	11.8	11.3

Table 4 Micro hardness results (with standard deviation of ±50 (HVN1000)) for lines *A*1, *A*2 and *A*3 at low cooling rate (closed-loop control at 430 $\frac{°C}{s}$)

Sample no.	*A*1	*A*2	*A*3
Micro hardness (HVN1000)	330	301	336

All three lines in sample *A* have a similar microstructure in terms of: (1) grain size, (2) cellular dendrite growth, (3) volumetric percentage of the columnar and cellular regions, and (4) volumetric percentage of the γ-austenite and δ-ferrite phases (white and dark regions of the micrographs shown in 12). Thus, by implementing a closed-loop control for the cooling rate during multi-track claddings in sample *A*, their microstructures were controlled consistently throughout the deposition. Although, the micrographs indicate very similar microstructures, quantitative measurements of the grain structures are required to verify their consistency.

Stainless steel has a granular structure when solidified in its primary austenite phase. Hence, similar microstructures of stainless steel depositions should have similar grain size values. In order to quantitatively compare the influence of the cooling rate on microstructures, the grain size (or solidified dendrite cell size) of each cladding was measured as mentioned in the following paragraphs.

The ASTM grain size number was measured for the low cooling rate region, $C = 430\frac{°C}{s}$, (Fig. 11). The Heyn [25] lineal intercept procedure was used to obtain the ASTM grain size of the *A* samples. In this procedure three concentric circles were sketched on a random location of each sample and the number of grain boundary intersections with the circles, *P*, were counted. By dividing *P* with the actual length of the circles, *L*, the number of grain boundary intersections per unit length of the test line, P_L, is obtained. The mean lineal intercept length, *l*, is obtained as follows:

$$l = \frac{1}{P_L} \tag{2}$$

which has a unit of millimeters. Finally, the ASTM grain size number, G_d, is derived by the following:

$$G_d = (-6.643856\log l) - 3.288. \tag{3}$$

Table 5 Micro hardness results (with standard deviation of ±50 (HVN1000)) for lines *A*1, *A*2 and *A*3 at high cooling rate (closed-loop control at 850 $\frac{°C}{s}$)

Sample no.	*A*1	*A*2	*A*3
Micro hardness (HVN1000)	426	439	467

Fig. 13 Clad cross section in LAM [26]

The ASTM grain size number of each line in the *A* sample is listed in Table 3. According to Table 3, all the *A* lines have similar grain size values, which indicates consistent microstructure produced by the real-time microstructure controller.

Considering that at high cooling rates, $C = 850\frac{°C}{s}$, (Fig. 12) the *A* samples exhibited a needle-like martensite microstructure within the boundaries of the as-cast cellular structure, and so the grain sizes could not be directly related to the austenite/ferrite dendrite structures. However, it is obvious that based on the presence of martensite, a high cooling rate has been achieved with a consistent microstructure throughout the process.

It is noteworthy to point out that although the melt pool temperature is constant for both cooling rate regions (Fig. 8), the microstructures of the low cooling rate (Fig. 9) is different to that of the higher cooling rate (Fig. 10). Hence, it is concluded that maintaining a constant melt pool temperature does not lead to a similar microstructure, and instead the cooling rate has a direct correlation with microstructure. This is to the contrary of the majority of reports available in literature, which have investigated thermal and material control of the process.

Moreover, in all the *G* lines, the low cooling rate region ($430\frac{°C}{s}$) has a larger grain size compared to the higher cooling rate region ($850\frac{°C}{s}$), which is in complete agreement with the information provided in literature.

2.1.2 Micro hardness analysis in closed-loop control of the microstructure

To further assess the microstructure obtained by the real-time closed-loop microstructure controller, micro hardness tests were performed on the deposited clad lines in sample *A* as shown in Tables 4 and 5. It is noted that all microhardness tests were performed at similar locations for all samples at the top of the clad cross section and a minimum number of three measurements were averaged to report the final value.

Another indication of a controlled microstructure is the similar hardness values measured for all deposited samples. According to results listed in Table 4, all the *A* samples have similar hardness results at low ($430\frac{°C}{s}$) and high cooling rate ($850\frac{°C}{s}$) regions. In other words, Tables 4 and 5 indicate a significant approval of microstructure control for the deposited lines at both cooling rate regions. Interestingly, all the *A* specimens have a similar microhardness related to their consistent microstructures. Overall, hardness tests further support the correct functionality of the real-time microstructure controller for the LAM process.

Moreover, the consistent hardness values of the depositions indicate one of the several applications of the developed real-time microstructure controller. Using such a controller, one can produce consistent desired mechanical properties (e.g., hardness and wear) at different locations of a product, tailored to specific requirements (Figs. 11 and 12).

2.1.3 Dilution and clad height analysis in closed-loop control of the microstructure

Although, results indicate that the microstructure has been controlled in real-time by the developed closed-loop system, the controller's effect on physical properties (e.g., clad height and dilution) should also be compared. The clad height and dilution of the *A* samples were measured to analyze the effect of cooling rate and melt pool temperature on these parameters. In Fig. 13, h is the clad height, w is the clad width, θ is the angle of wetting, and b is the clad depth representing the thickness of substrate melted during the cladding and added to the clad region. The geometrical definition of dilution is defined as follows:

$$\text{dilution} = \frac{h}{h+b} \tag{4}$$

The clad height and dilution for the *A* samples are presented in Table 6. A consistent dilution and clad height is observed in all deposition lines of the *G* sample, which is due to the consistent performance of the microstructure controller. Thus, a

Table 6 Dilution and clad height of the *A* sample for two cooling rate set-points

Sample	$A1\left(430\frac{°C}{s}\right)$	$A1\left(850\frac{°C}{s}\right)$	$A2\left(430\frac{°C}{s}\right)$	$A2\left(850\frac{°C}{s}\right)$	$A3\left(430\frac{°C}{s}\right)$	$A3\left(850\frac{°C}{s}\right)$
Clad height (μm)	138	75	145	70	140	86
Dilution (%)	18	38	16	41	18	39

closed-loop microstructure process with a constant cooling rate results in a controlled clad height and dilution.

However, the low (430 $\frac{°C}{s}$) and the high cooling regions (850 $\frac{°C}{s}$) have different dilution and clad height values in Table 6. The different clad height and dilution is a concern since many applications require different desired microstructures with a constant geometry. The changing clad height for different closed-loop microstructure responses requires further attention and analysis.

The cooling rate and microstructure measurements demonstrate that solidification structures produced by the LAM process can be controlled using a closed-loop control process. The controller developed here is the first of its kind in the LAM industry, since it can produce microstructures with a desired grain size, cellular and columnar regions, volumetric percentage of the columnar and cellular regions, and volumetric percentage of different phases in real-time. The growth of the cellular and columnar regions during metal deposition may also be controlled based on the cooling rate. Moreover, the volumetric percentage of each phase of the deposition can be controlled and set in situ during deposition. The applications of the developed microstructure controller are quite broad and can be applied to various industries and applications.

3 Conclusion

The purpose of the current study was to develop a real-time monitoring system and closed-loop process for real-time microstructure control in laser additive manufacturing. An infrared-based feedback signal was designed for monitoring the cooling rate and melt pool temperature of the process in real-time. An IR camera was used to provide online thermographic images of the LAM process. With the help of thermal image analysis techniques, thermal images were processed in real-time to obtain thermal information of the process. This information includes: (1) melt pool temperature, (2) real-time cooling rate, and (3) thermal maps (1-D, 2-D, and 3-D).

A closed-loop PID controller was established to control the cooling rate in the LAM process. The controller was designed to control the cooling rate around operating points in order to achieve a novel closed-loop microstructure controller. The closed-loop process was evaluated in multi-track LAM depositions with a staircase set-point. The controller performance was satisfactory in achieving the desired cooling rates in real-time. More importantly, it was observed that the multi-tracks with similar cooling rates, which were deposited adjacent to each other had consistent similar microstructures due to the controlled cooling rate.

The developed controller is a breakthrough in the LAM industry, since it can provide controlled microstructure and morphology in real-time. The growth of the cellular and columnar regions during metal deposition may also be controlled based on the cooling rate. One of the most important capabilities of a real-time microstructure controller of this type is the ability to produce localized desired mechanical and metallurgical properties in the final product.

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